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NATURAL PERIOD CHARACTERISTICS OF SELECTED TREE SPECIES

DIVISION OF FIRE RESEARCH
FOREST SERVICE
U. S. DEPARTMENT OF AGRICULTURE

ACKNOWLEDGMENT

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by

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SUMMARY

Prediction of wind breakage in forest stands requires information on the natural period characteristics of the tree system. An experimental program started in 1951 has led to a number of generalized relations which are useful in determining period characteristics for a wide range of tree species and stem diameters.

Two hundred and eighty-four trees including 217 conifers, 37 broadleafs, and 30 palms were tested for natural period. Bare stem periods of several of the trees were also determined. Periods were taken by timing manually induced vibrations with a stopwatch.

The results are presented by plotting for various groups, the natural period of the trees and stems as a function of stem height and diameter. The period relations of these groups were all highly significant.

The natural period relation of the broadleafs and palms averaged higher than that of the conifers whereas the bare stem period relation was approximately one-half of that for the trees.

Neither site nor normal crown length were found to effect period to any considerable degree. Differences in crown mass concentration and natural crown weight differences for a given crown length along with differences in stem form, density, and modulus of elasticity, which were not considered, seem to account in part for the variation in period.

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INTRODUCTION

A study of the natural periods[1/] of trees is one of a number of studies (1,4,6,7,10)[2/] being conducted in the course of developing a scheme which predicts blast damage to forest trees and stands.

Analysis of damage to trees by blast of the type associated with atomic weapons (2,8) indicates that trees are a drag-type target by virtue of their long natural periods and the relatively short time required for shock to equalize around crown components. Trees deflect under aerodynamic drag action of aftershock winds on foliage, branchwood, and main stem surfaces; this motion is resisted by inertial forces.

Relating natural periods to measurable physical characteristics of trees would allow specification of relations applicable to a wide range of tree species and stem diameters. This study was started to investigate, for trees and bare stems of selected species, the relation between natural periods and physical properties of the stems.

A survey of literature yields no information on period characteristics of naturally rooted trees. This is not surprising since past investigations of wind damage to trees have been limited largely to observations or to study of the mechanical aspects of wind breakage on a static basis (3,5,12). An investigation (9) of storm-gust damage to cross-arm weighted cedar telephone poles, averaging 40 feet in length and 13 1/2 inches in diameter at the ground surface, showed natural periods to be close to 2 seconds.

PROCEDURE

This study is based on an analysis of 284 trees including 217 conifers, 37 broadleafs, and 30 coconut palms. Nine conifer species from three sites and three states, and seven broadleaf species from two sites and two countries are represented. Tables 1 and 2 list species, give the site classes, and describe locations from which sample trees were selected.

Trees were chosen to represent important species for the locations listed in tables 1 and 2. Criteria for individual tree selection were dominance, uniformity and fullness of crown, and absence of defects visible from the ground, i.e., fire scars, rot, crook, sweep, and fork. Diameter at breast height ranging from 4 inches to 36 inches were sought for the conifers; a smaller diameter limit was tolerated for broadleaf species owing to their generally slower growth. For some species certain diameter classes were not available, and in other species, limited data were unavoidable as other studies (1,4,6,7,10) dictated the choice of trees. Periods were taken for all the trees selected for analysis, but not all of the trees were tested for bare stem periods.

1/ Time, in seconds, required for one complete cycle of oscillation.

2/ Underlined numbers in parentheses refer to Literature Cited, page 34.

Table 1.--Site situation of test trees--conifers

Tree numbers	Species	Location	Site[1/] class	Crown canopy
1-6	Ponderosa pine (Pinus ponderosa)	Shasta Exper. Forest, Shasta-Trinity Natl. For., Calif. Elev. 4000 ft (Westside)	II	Semi-open
7	Ponderosa pine (Pinus ponderosa)	Shasta Exper. Forest, Shasta-Trinity Natl. For., Calif. Elev. 5000 ft (Eastside)	II	Semi-open
8-19	Ponderosa pine (Pinus ponderosa)	Stanislaus Natl. Forest, Calif. Elev. 4000 ft (Westside)	II	Semi-open
1-170	Ponderosa pine (Pinus ponderosa)	Charleston Ranger Dist., Nev. Natl. Forest, Nev. Elev. 8000 ft.	IV-V	Semi-open
1	Sugar pine (Pinus lamber-tiana)	Shasta Exper. Forest, Shasta-Trinity Natl. For., Calif. Elev. 4000 ft (Westside)	II	Semi-open
2	Lodgepole pine (Pinus contorta)	Shasta Exper. Forest, Shasta-Trinity Natl. For., Calif. Elev. 4000 ft (Westside)	II	Semi-open
3-9	Loblolly pine (Pinus taeda)	Santee Exper. Forest, Francis Marion Natl. For., S.C. Elev. 300 ft	II	Closed
10	White fir (Abies concolor)	Shasta Exper. Forest, Shasta-Trinity Natl. For., Calif. Elev. 4000 ft (Westside)	II	Closed
11	Douglas-fir (Pseudotsuga taxifolia)	Shasta Exper. Forest, Shasta-Trinity Natl. For., Calif. Elev. 4000 ft (Westside)	II	Closed

1/ Site--capacity to produce forests as reflected by average height of dominant and codominant trees; Site I highest capacity.

Table 1 (Continued)

Tree numbers	Species	Location	Site[1] class	Crown canopy
12	Incense cedar (Libocedrus decurrens)	Shasta Exper. Forest, Shasta-Trinity Natl. For., Calif. Elev. 4000 ft (Westside)	II	Open
13-18	Engelmann spruce (Larix occidentalis)	Priest River Exper. For., Kaniksu Natl. For., Ida. Elev. 3000 ft	III	Closed
25-28	Western white pine (Pinus monticola)	Priest River Exper. For., Kaniksu Natl. For., Ida. Elev. 3000 ft	III	Closed

1/ Site--capacity to produce forests as reflected by average height of dominant and codominant trees; Site I highest capacity.

All tests were conducted under dry soil conditions except for those of loblolly pine and the eastern broadleafs. The latter species were tested under moist soil conditions. Analysis of most of the trees were made in mid- or late summer before leaf fall; pisonia and the palms were tested in the spring during the dry season when foliage volume was near its annual minimum.

For each tree selected for testing, total height[3], diameter breast height[4], and description of the location and site class were recorded. The natural period of the tree stem was determined by timing repeated oscillations with a stopwatch, and averaging. The tree was set in motion manually by pulling on a light line attached to the upper part of the stem, force being applied to the line in resonance with the natural period of the tree. The natural period of the stem was determined in a similar manner after the tree was completely pruned of branches (figure 1).

For some of the trees (7 ponderosa pines from Shasta National Forest) a modified testing procedure was used in order to determine the effect of crown length on the natural period of the tree. Using total height, the tree was divided into sections of 20 percent and the base of the crown trimmed to the nearest 20 percent (see figure 2). After recording the "full-crown" period, the lower 20 percent section of the crown was pruned and the period again measured. Similarly, period measurements were made after each succeeding crown section was removed.

3/ Total height is stem length (from tip) to 1 foot above ground level.

4/ Breast height is 4 1/2 feet above ground level.

Table 2.--Site situation of test trees--
broadleafs and palms[1/]

Tree numbers	Species	Location	Site[2/] class	Crown canopy
1-4	Silver maple (Acer saccharinum)	Pisgah Natl. Forest, N.C., Elev. 2300 ft	II	Closed
5-10	Sweet birch (Betula lenta)	"	"	"
11-16	Pignut hickory (Carya glabra)	"	"	"
17-20	American beech (Fagus grandifolia)	"	"	"
21-26	Yellow-poplar (Liriodendron tulipifera)	"	"	"
27-31	Scarlet oak (Quercus coccinea)	"	"	"
32-37	Pisonia (Pisonia grandis)	Bikini Atoll, N. Marshall Is., American Trust Territory Elev. 5 ft	Good	"
38-67	Coconut palm (Cocos nucifera)	"	"	"

1/ The palms are in the palm family of the Monocotyledon class in the plant kingdom. The trees listed as broadleafs are in the Dicotyledon class. Both are in the same plant kingdom subdivision (Angiosperms), however, whereas the conifers are in the subdivision Gymnosperms.

2/ Site--capacity to produce forests are reflected by average height of dominant and codominant trees; Site I highest capacity.

(A) (B)

Figure 1.--Tree conditions for period determination of (A) full-crown tree (B) tree stem, tree no. 5, ponderosa pine.

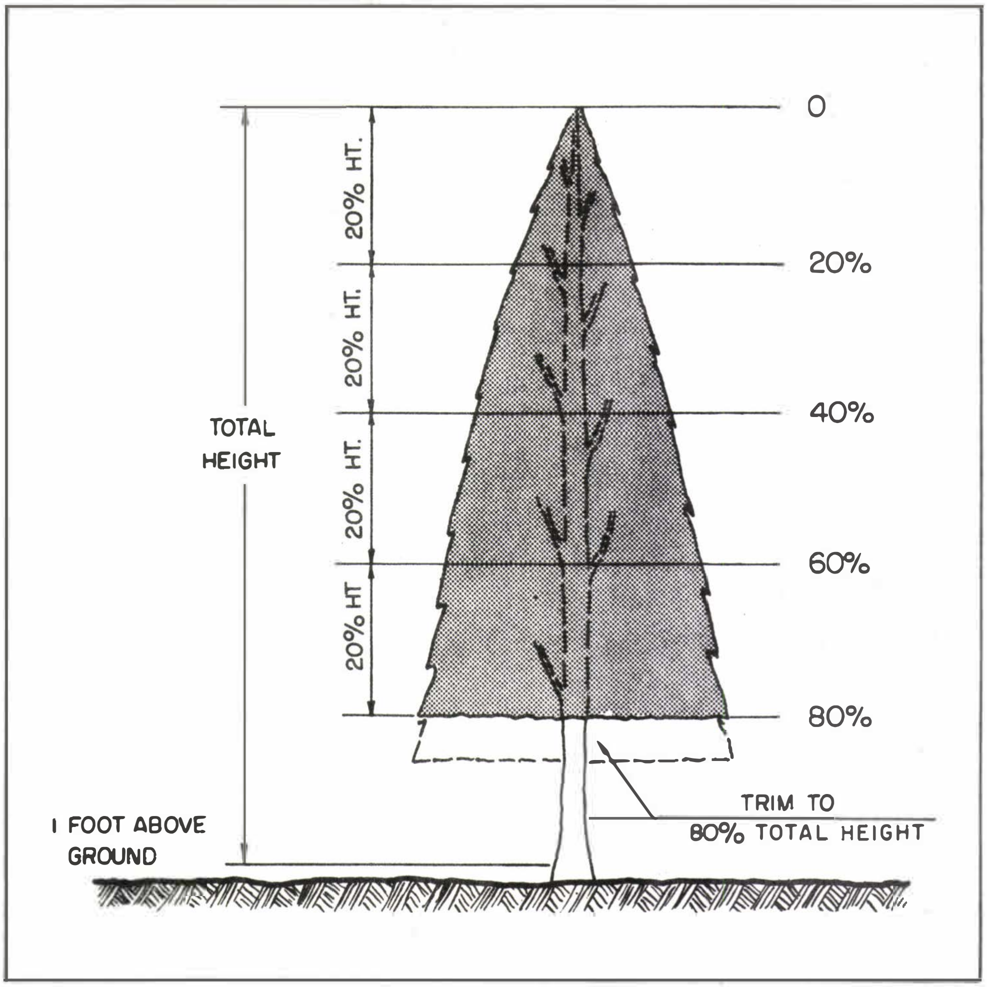

Figure 2.--Tree division for crown length-period analysis

RESULTS

For purposes of analysis the data of this study were grouped into the following 6 categories:

1. Ponderosa pine, 20 percent crown segments
2. Good site ponderosa pine
3. Poor site ponderosa pine
4. All conifers (except ponderosa pine)
5. Broadleafs and coconut palms
6. Bare stems, all species

Grouping of the data was based on the crown geometry of the trees and the site conditions from which the trees were taken.

Tables 4-9, Appendix, present, for each of the above groups, respectively, data on the physical characteristics of the crown and stem of each tree tested. The natural periods of the trees and stems are tabulated in the Appendix in tables 4-8 and table 9 respectively.

The natural period of a tree stem, closely representing a conical rod with its tip free and the base fixed, can be approximated with the equation (11)

$$\tau = c\,\frac{L^2}{d}\sqrt{\frac{E}{\rho}} \qquad (1)$$

where

c = stem form or shape factor

d = diameter of stem at base

E = modulus of elasticity

L = stem length

τ = natural period

ρ = mass density

If it is assumed that the effects of stem form, density, and modulus of elasticity are small compared with the effects of height and diameter then the natural period can be expressed as a function of the height and base diameter only. Thus equation (1) for a tree with $L = H_{bh}$ and $d = d_{bh}$ may be replaced by the more general equation

$$\tau = f\left(\frac{H^2_{bh}}{d_{bh}}\right) \qquad (2)$$

The measured periods τ were plotted against values of $\left(H_{bh}\right)^2 / d_{bh}$ for the various groups of trees and bare stems. The results are presented in figures 3 to 8 inclusive. Regression equations in the form of $\tau = a + b\left(H_{bh}\right)^2 / d_{bh}$ were determined for each group. Equation constants a and b and statistics for each group are tabulated in table 3.

Table 3.--Regression constants and statistics for natural period relations

Group	Description	Crown	Regression constants		Statistical measures	
			a	b	r[1]	Syx[2]
1	Ponderosa pine	0%	0.62	0.00040	0.994	0.079
	" "	20%	0.90	0.00044	0.986	0.134
	" "	40%	1.03	0.00056	0.986	0.170
	" "	60%	0.99	0.00062	0.982	0.213
	" "	80%	1.02	0.00062	0.984	0.197
	" "	40%, 60% 80%	1.02	0.00060	0.981	0.187
2	Good site ponderosa pine	Full	1.12	0.00053	0.740	0.557
3	Poor site Nevada ponderosa pine	Full	1.00	0.00053	0.732	0.436
4	Ponderosa pine, good and poor site	Full	0.94	0.00056	0.873	0.271
5	Broadleafs and coconut palms	Full	1.68	0.00050	0.882	0.600
6	Bare stems all species	0%	0.63	0.00023	0.796	0.373

1/ Coefficient of correlation.
2/ Standard error of estimate.

Figure 3 presents the period relation of several ponderosa pines with different crown segments. These trees are also plotted with several other ponderosa pine for the period relation of good site trees (figure 4). Period values for poor site ponderosa pine are not plotted individually; only the curve for the period relation is presented (figure 5).

The periods of various conifers other than ponderosa pine are plotted in figure 6 along with the combined curve for the period relation of ponderosa pine. No attempt was made to calculate the regression, since species variation was the only interest.

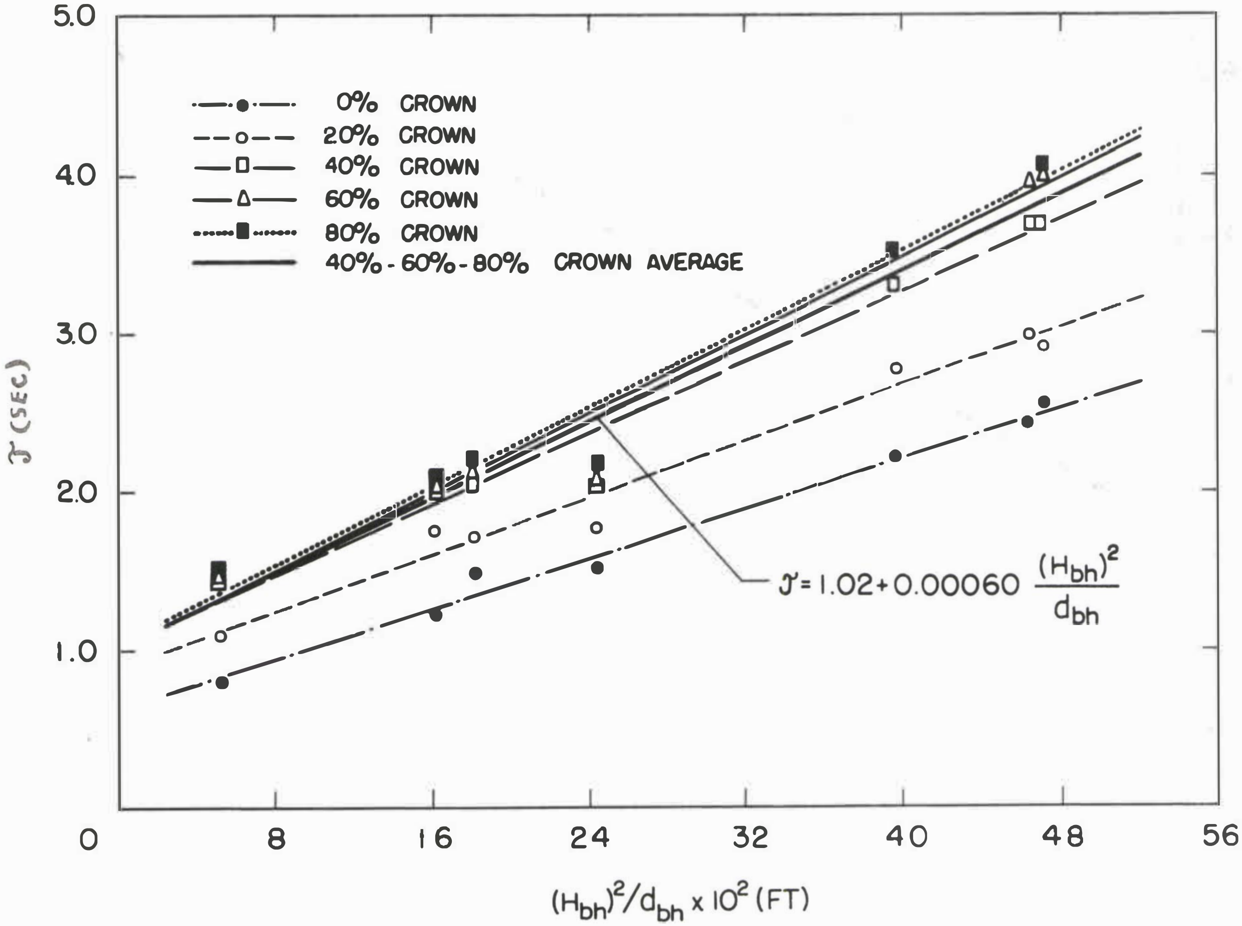

Figure 3.--Natural period--crown length relations for ponderosa pine

The natural period relation of the broadleafs and coconut palms is presented in figure 7. Even though the palms and broadleafs are found in two different classes in the plant kingdom, the palms were plotted with the broadleafs because of similarities in crown geometry.

Bare stem periods for all tree species tested are plotted in figure 8. The natural period relation was determined for all the tree stems treated as a group. No attempt was made to differentiate separate period relations of different species.

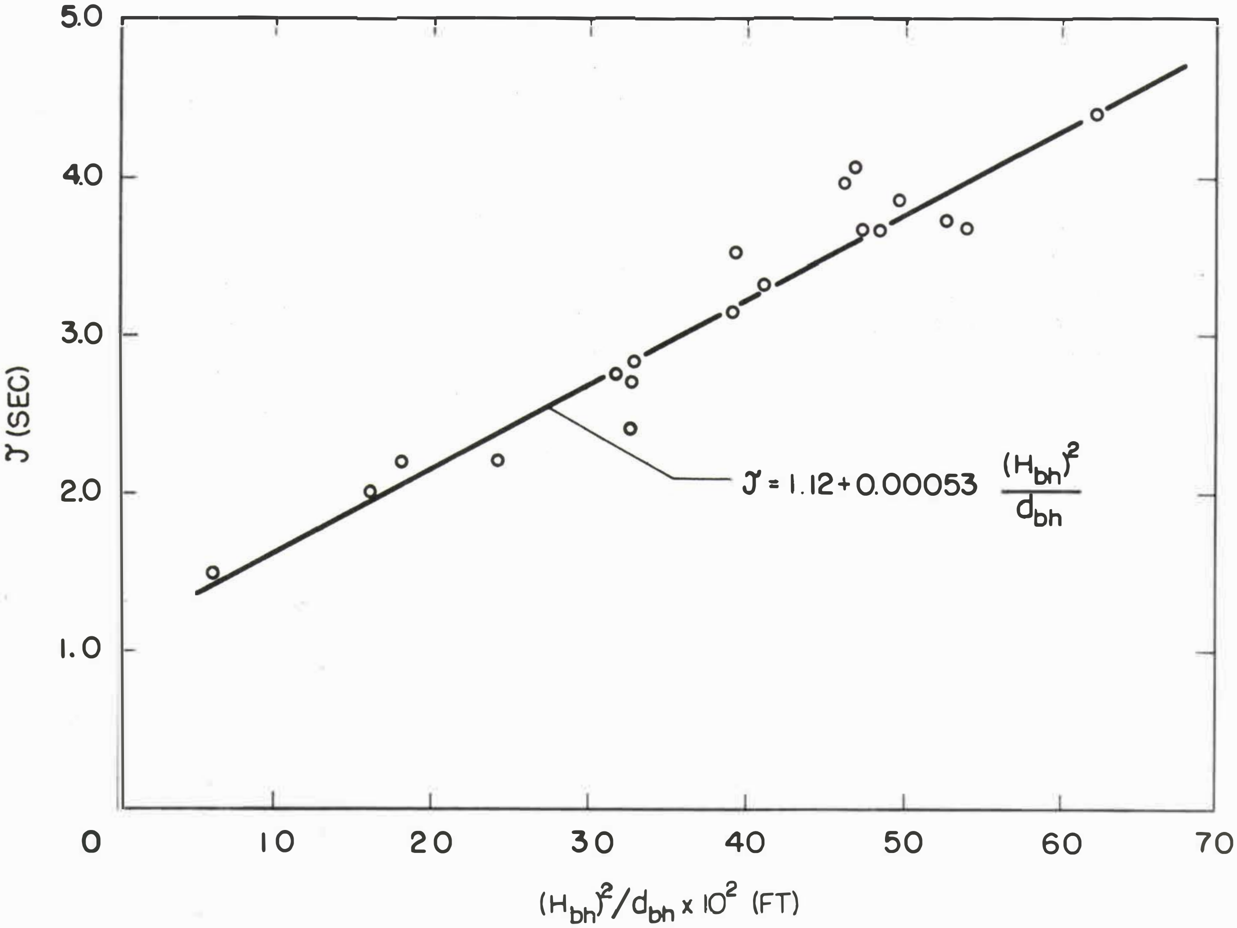

Figure 4.--Natural period relation of good site ponderosa pine

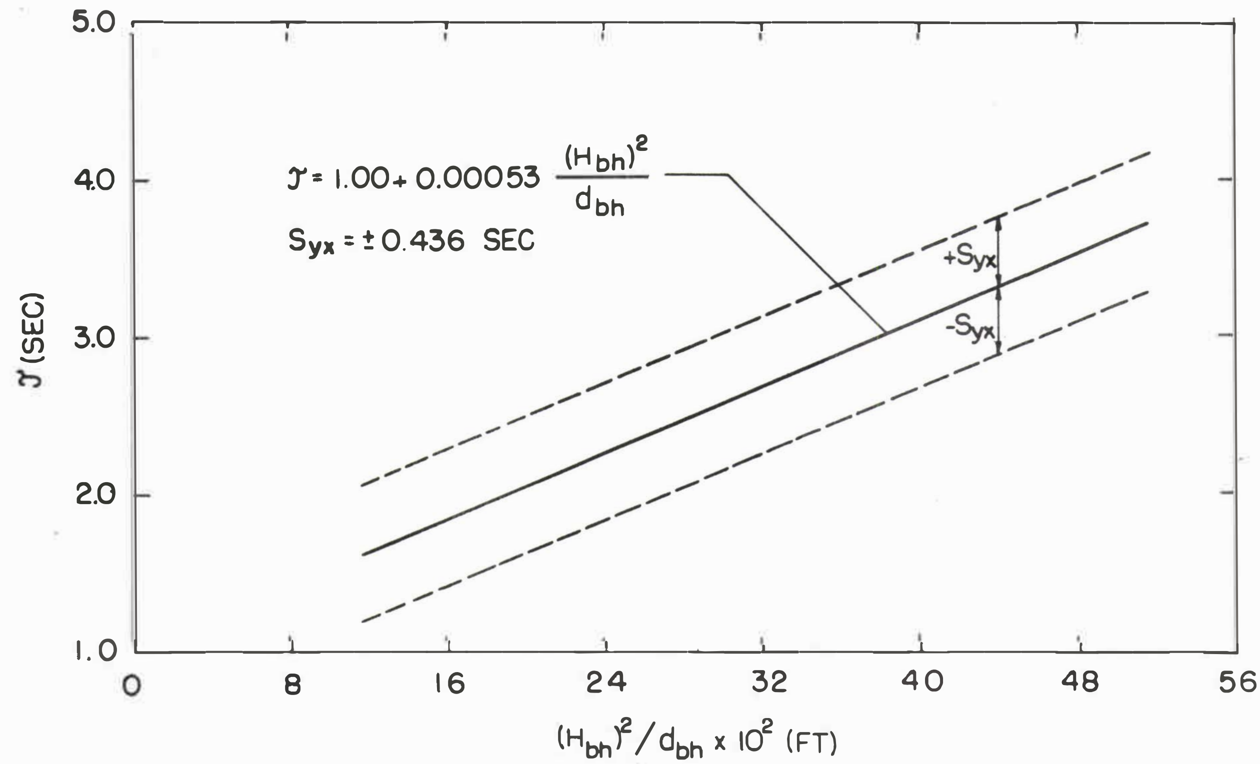

Figure 5.--Natural period relation of poor site ponderosa pine

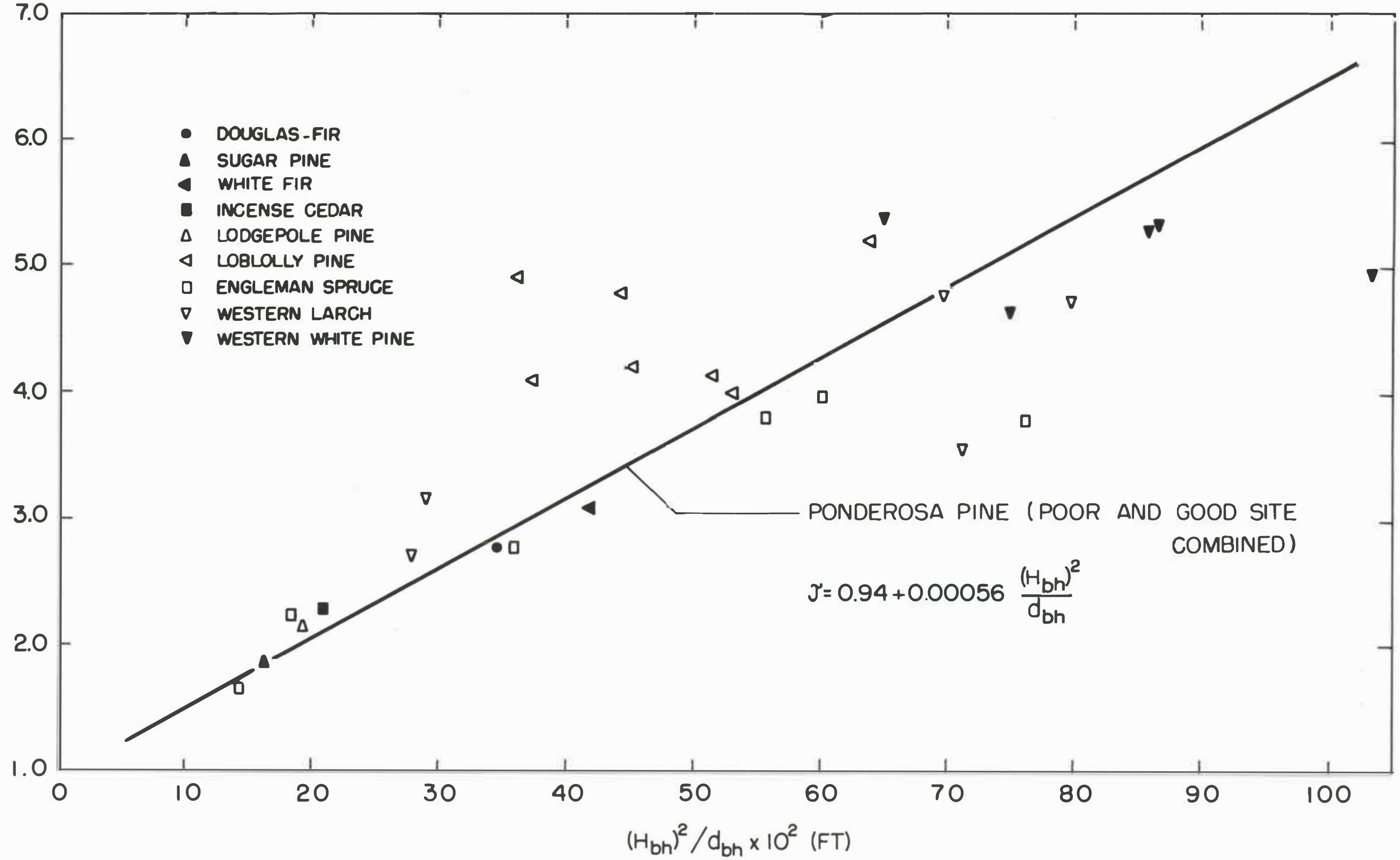

Figure 6.--Comparison of natural period of several conifers with the natural period relation for ponderosa pine

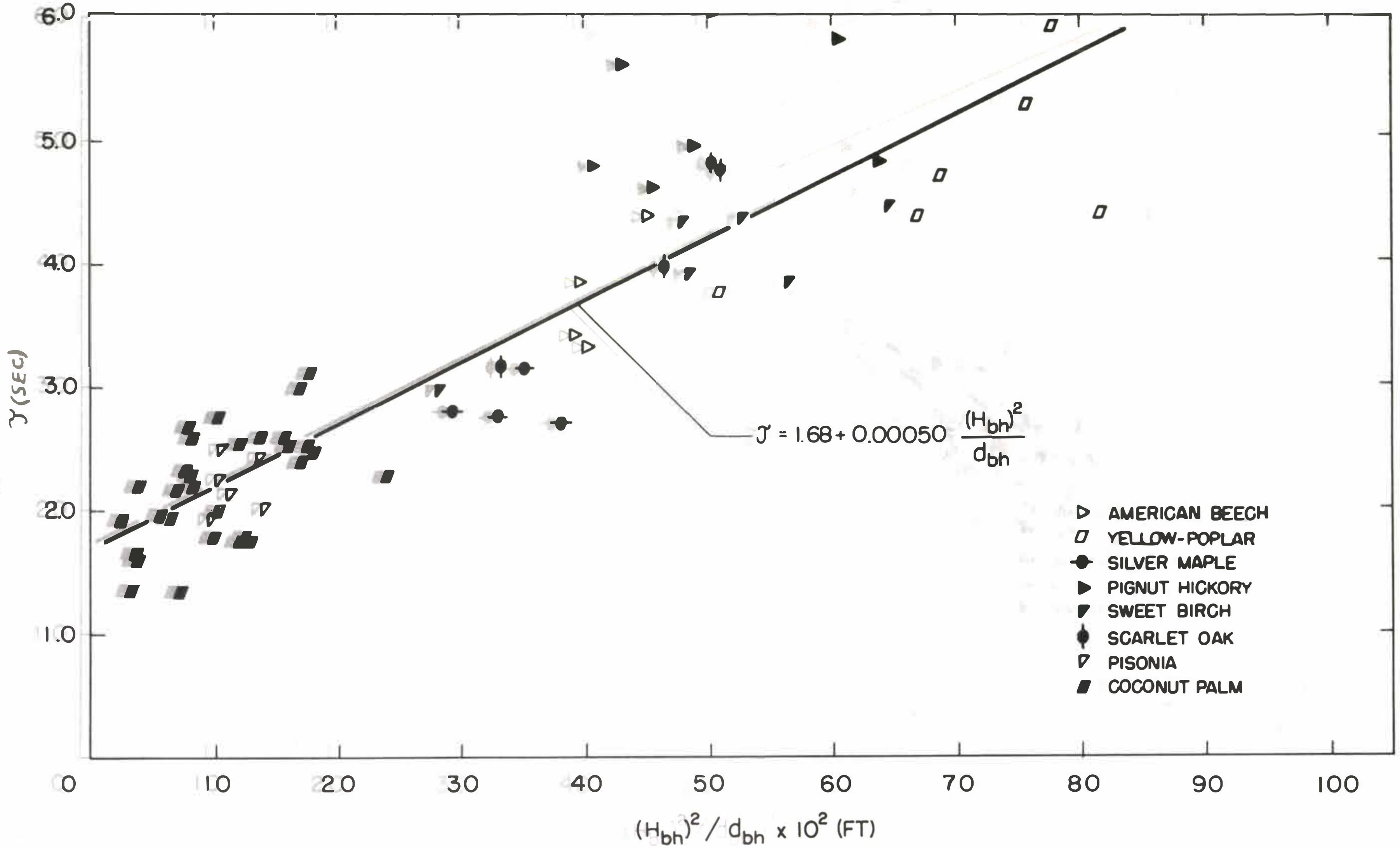

Figure 7.--Natural period relation of broadleafs and coconut palms

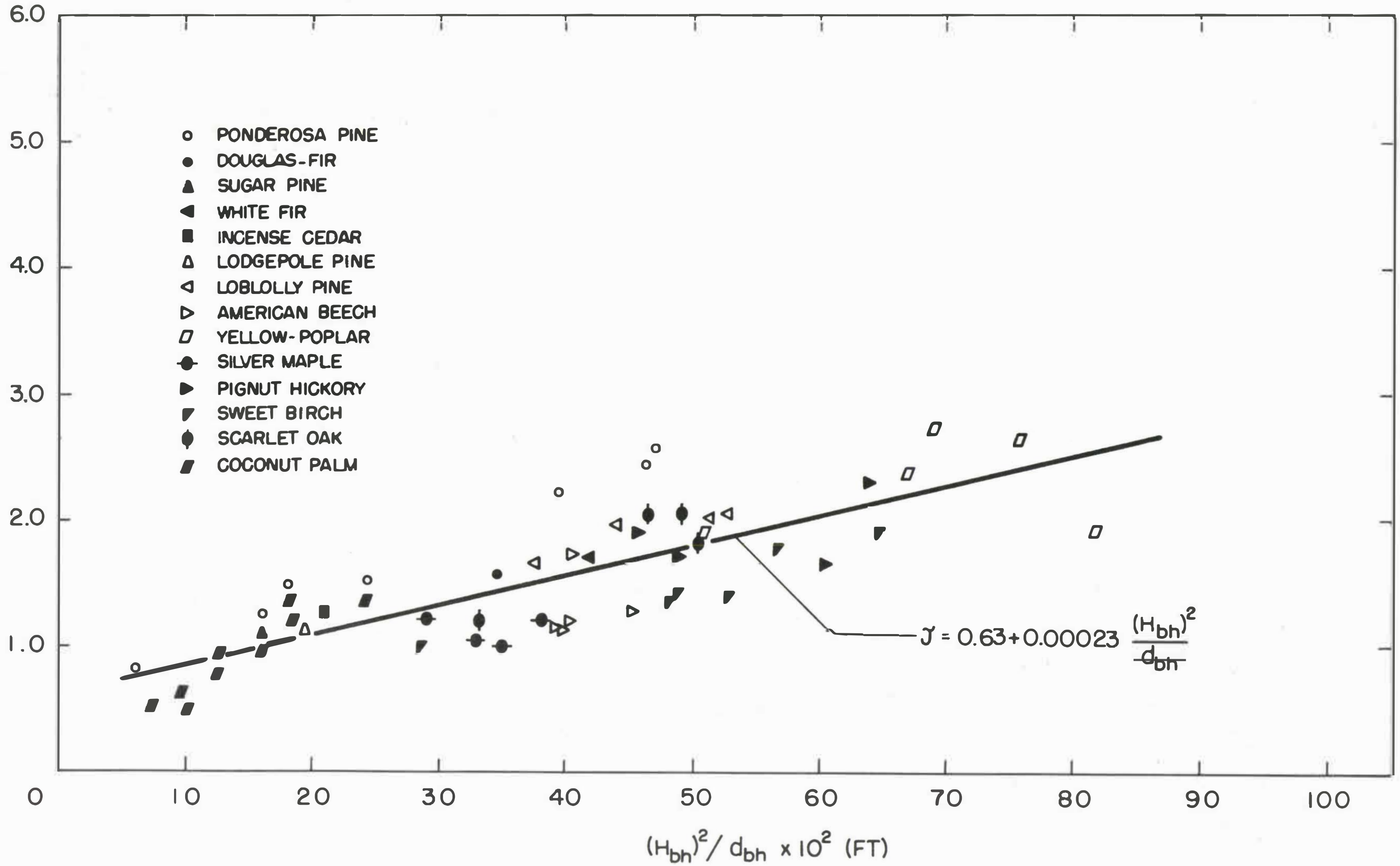

Figure 8.--Natural period relation of bare stems for several tree species

DISCUSSION

From the curves presented in figure 3 it can be seen that successive reduction in crown length resulted in a decrease in the natural period of the trees tested. The greatest decrease was exhibited by the bare stems of these trees. The decreases observed were due in part to the lowering of the mass concentration of the trees.

It is interesting to note that a significant decrease in the period did not occur until after the crowns were reduced to 20 percent. Data for 80, 60, and 40 percent crowns were found to plot quite close together. This would seem to indicate that for trees with crowns in the normal length range of 40-80 percent, crown length has no significant effect on period, and the natural period can be estimated from an average curve drawn through these points (see figure 3 and table 3).

The natural period relation for 20 percent crown is presented in figure 3 for completeness only. Trees with such small crowns are seldom, if ever, found in nature. Furthermore, at this crown percent uniform oscillations of the entire tree system were difficult to obtain. The upper third of the stem had a tendency to vibrate in more than one plane, i.e., exhibited a Lissajous' motion.

It can be seen from a comparison of the equation constants (table 3) for the natural period relations of good and poor site ponderosa pine (figures 4 and 5) that the period relations of these two groups of trees are not significantly different. The regression line of one group superimposes nearly perfectly on the other. From these results the indications are that site is a relatively unimportant determinant of tree period, and period determinations can be estimated from a combined curve (see figure 6).

Plotting period values for the other conifer species (table 7, Appendix) on the combine curve for ponderosa pine (figure 6) gave strong indications that the periods of the conifers were comparable to those of the pines. It should be noted however, that the plotted points do vary somewhat from the curve of ponderosa pine. Such variations are not too unexpected when the fact is considered that large differences in period can also be seen in trees of the same species having similar stem characteristics. These differences may be attributed in part to differences in stem form, density, and modulus of elasticity that can be found within and among the tree species tested. Also, differences in crown mass concentration and crown geometry contribute to the observed variations. Even with these inconsistencies however, the natural period can be estimated reasonably well for other conifer species from the curve for ponderosa pine.

Broadleafs, unlike conifers, generally have a more bushy habit of crown growth. This permits greater concentration of crown mass in a shorter crown length. Although the palms are from a different class in the plant kingdom, they are quite similar to the broadleafs in crown

geometry. As in the broadleafs, the crowns of the palms are more or less concentrated at the apex of the stem. Because of this, the palms were grouped with the broadleafs for analysis (see table 8, Appendix, and figure 7).

Examination of table 3 reveals that the natural period relation of the broadleafs and palms averaged higher than that of the ponderosa pines. The differences in the crown mass concentration of the broadleafs and palms may be a partial explanation for the observed higher period relation. Concentrating the mass of the crown in a shorter crown length has the same effect as raising the mass concentration of the whole tree to a higher point along the stem. Trees in this condition will tend to have longer periods of vibration than trees with more evenly distributed crowns.

Within the broadleaf group (figure 7) variations in tree period can be seen for trees with similar stem dimensions. These variations are present within the same species as well as between various species. Individual differences in stem form, density, and modulus of elasticity, which are known to exist within and among the species tested, may well explain the observed variations. Also, the deliquescent branching habits may help explain some of these differences. The large limbs making up the crown, each having a different period, tend to vibrate independently and oppose or reinforce each other in some random manner while the tree is in motion. Under these conditions variations in period are to be expected.

As in the case of ponderosa pine (see figure 3), complete removal of the crowns of the various tree species (table 9, Appendix) caused a marked decrease in period (see figure 8). From equation constants tabulated in table 3, the bare stem period relation can be seen to be about one-half of that of the trees. A major part of the period reduction may be attributed to the lowering of the mass concentration of the vibrating body with crown removal.

It can be further seen from a comparison of the period plot for bare stems (figure 8) and those for the coniferous trees (figure 6) and broadleaf and palm trees (figure 7) that the variations exhibited by the trees were reduced considerably after the crowns were removed. Variations in period of the bare stems are due mainly to differences in stem form, density, and modulus of elasticity.

CONCLUSIONS

1. The results of this study permit the determination of the natural periods of trees and stems from the stem height and diameter.

2. Crown length has no significant effect on tree period when the length of crown is in the range of 40-80 percent of stem height; a decided decrease in period occurs for smaller crown lengths.

3. Crown mass concentration and natural crown weight differences for a given crown length along with differences in stem form, density, and modulus of elasticity explain in part the variations in period.

4. The natural period relation of the broadleafs and palms averages higher than that of the conifers.

5. Periods of bare stems are about one-half of that for crowned trees.

6. Site is a relatively unimportant determinant of tree period.

APPENDIX

EXPERIMENTAL FIELD DATA

Table 4.--Experimental tree period data[1/] for ponderosa pine, 20 percent crown segments

Tree number	d_{bh} (ft)	H_{bh} (ft)	Age (yrs)	Percent crown	H_c (ft)	τ (sec)
1	0.75	34.8	-	0	0	1.24
				20	7.7	1.77
				40	15.3	2.02
				60	23.0	2.03
				80	30.7	2.00
2	0.79	37.8	40	0	0	1.48
				20	8.2	1.73
				40	16.5	2.09
				60	24.7	2.15
				80	33.0	2.19
3	0.42	14.6	43	0	0	0.81
				20	3.6	1.10
				40	7.2	1.41
				60	10.7	1.47
				80	14.3	1.49
4	1.25	55.2	54	0	0	1.51
				20	11.8	1.77
				40	23.5	2.06
				60	35.3	2.07
				80	47.0	2.19
5	1.90	56.0	56	0	0	2.21
				20	18.0	2.78
				40	36.0	3.33
				60	54.0	3.45
				80	72.0	3.51
6	3.08	120.5	-	0	0	2.56
				20	24.7	2.93
				40	49.5	3.70
				60	74.2	3.98
				80	99.0	4.05
7	1.69	88.5	199	0	0	2.43
				20	18.4	2.99
				40	36.8	3.71
				60	55.2	3.95

1/ Nomenclature given on page 36.

Table 5.--Experimental tree period data[1/] for good site ponderosa pine

Tree number	d_{bh} (ft)	H_{bh} (ft)	Age (yrs)	Percent crown	H_c (ft)	τ (sec)
1*	0.75	34.8	-	80	30.7	2.00
2*	0.79	37.8	40	80	33.0	2.19
3*	0.42	14.6	43	80	14.3	1.49
4*	1.25	55.2	54	80	47.0	2.19
5*	1.90	56.0	56	80	72.0	3.51
6*	3.08	120.5	-	80	99.0	4.05
7*	1.69	88.5	199	60	55.2	3.95
8	1.88	95.7	107	40	40.1	3.66
9	1.57	86.3	87	40	36.3	3.67
10	2.04	101.0	87	60	63.3	3.84
11	1.41	74.3	79	40	31.5	3.14
12	1.57	91.0	83	40	38.2	3.72
13	2.00	111.8	87	60	69.8	4.38
14	1.10	59.9	81	60	38.6	2.40
15	1.52	70.3	119	40	29.9	2.70
16	1.16	79.1	73	40	33.4	3.66
17	1.89	88.3	110	40	37.1	3.30
18	1.10	59.0	74	40	25.4	2.74
19	1.09	59.9	76	60	38.6	2.82

1/ Nomenclature given on page 36.
* These trees are also tabulated in table 4.

Table 6.--Experimental tree period data[1/] for poor site ponderosa pine

Tree number	d_{bh} (ft)	H_{bh} (ft)	Age (yrs)	Percent crown	H_c (ft)	τ (sec)
1	0.78	38.5	170	63	26.6	2.01
2	1.34	60.3	175	69	44.1	2.43
3	0.86	36.0	90	78	30.8	1.72
4	0.74	36.1	165	63	24.8	1.76
5	1.08	48.0	165	57	29.1	2.29
6	1.42	54.3	185	42	24.1	2.19
7	0.99	56.4	195	36	21.3	3.65
8	1.08	61.0	170	49	32.8	3.25
9	1.47	57.3	275	75	45.3	1.91
10	1.51	70.6	127	46	34.1	2.62
11	1.34	70.9	256	62	45.8	2.72
12	0.97	40.8	75	83	36.8	1.76
13	1.12	43.0	65	78	43.8	2.01
14	1.10	40.3	110	77	33.8	1.79
15	1.20	51.2	158	76	41.4	2.12
16	1.00	50.5	174	69	37.0	2.45
17	1.13	50.0	145	66	35.3	2.20
18	1.16	48.2	152	66	34.2	2.33
19	1.19	54.0	245	76	43.7	2.29
20	1.42	56.3	258	75	45.0	2.19
21	1.20	55.2	290	86	50.7	2.32
22	1.28	53.8	250	69	39.4	2.01
23	1.35	53.7	170	59	33.6	2.97
24	1.23	77.6	233	56	45.4	3.13
25	1.30	64.9	230	77	52.6	2.87
26	1.10	59.1	250	64	40.0	2.77
27	1.23	58.4	168	44	27.3	2.27
28	0.91	43.9	145	58	27.6	2.38
29	1.08	54.1	140	72	41.3	2.33
30	1.22	58.2	251	77	47.7	2.15
31	1.11	47.2	135	66	33.6	2.36
32	1.31	51.1	184	79	43.4	2.27
33	0.75	42.0	129	67	30.4	2.00
34	0.98	37.0	149	71	28.9	1.60
35	1.32	57.7	187	60	36.8	2.02
36	1.10	51.7	195	74	40.9	2.20
37	1.08	51.1	170	61	33.2	2.60
38	1.19	59.2	170	65	41.4	2.67
39	1.03	49.9	196	52	27.8	2.37
40	1.11	45.5	185	55	26.9	1.94
41	0.89	39.5	182	65	27.9	1.99
42	1.44	54.8	206	64	37.4	1.96

1/ Nomenclature given on page 36.

Table 6 (Continued)

Tree number	d_{bh} (ft)	H_{bh} (ft)	Age (yrs)	Percent crown	H_c (ft)	τ (sec)
43	1.21	48.9	180	54	28.5	2.04
44	0.89	49.6	135	73	38.7	2.36
45	0.85	44.8	258	74	35.8	2.17
46	1.22	48.3	210	64	33.4	2.02
47	0.78	35.9	254	56	22.2	1.57
48	1.27	48.2	222	63	32.6	2.24
49	1.13	53.3	165	38	34.1	2.23
50	0.91	50.7	205	61	33.4	1.63
51	1.04	49.8	212	72	38.4	1.39
52	1.23	58.6	180	59	36.6	3.45
53	1.34	66.2	210	74	51.2	3.07
54	0.85	39.7	177	64	27.6	1.83
55	0.98	46.7	243	71	35.4	2.17
56	1.15	57.8	163	66	40.2	2.62
57	1.37	62.7	192	73	48.6	2.71
58	1.22	54.7	207	68	39.5	2.37
59	1.44	63.6	210	41	27.6	2.64
60	1.08	44.5	145	50	24.0	2.18
61	0.89	41.1	153	68	30.2	1.77
62	0.76	47.6	192	63	32.2	2.97
63	1.38	60.4	195	60	38.1	2.62
64	1.06	56.0	203	62	36.7	3.17
65	1.08	57.6	198	54	32.7	3.11
66	1.37	55.4	177	63	36.9	2.40
67	1.18	55.3	175	68	40.1	2.54
68	1.10	53.5	180	67	38.1	2.49
69	1.14	64.0	155	71	48.1	2.99
70	1.22	61.4	175	72	46.7	2.78
71	1.17	59.6	133	64	40.2	2.67
72	1.08	63.5	205	73	48.9	2.79
73	1.07	61.7	203	64	41.9	2.98
74	1.03	49.5	155	59	31.5	2.81
75	1.11	54.6	204	48	28.2	2.45
76	1.34	51.5	205	56	31.5	2.11
77	1.45	56.4	183	46	27.4	2.12
78	1.35	55.6	163	62	36.8	2.63
79	1.49	61.3	190	42	27.4	2.39
80	1.00	53.5	187	49	27.8	3.04
81	1.32	59.4	185	65	40.6	2.24
82	1.31	55.5	160	72	42.7	2.24
83	1.02	54.8	170	62	36.4	2.74
84	1.08	45.7	95	65	31.9	2.02
85	1.38	64.4	185	62	42.3	2.83

Table 6 (Continued)

Tree number	d_{bh} (ft)	H_{bh} (ft)	Age (yrs)	Percent crown	H_c (ft)	τ (sec)
86	1.29	57.6	155	63	38.5	2.45
87	1.21	59.1	178	67	41.8	2.18
88	1.34	64.5	251	68	46.0	2.45
89	1.34	52.9	260	60	33.9	1.60
90	1.00	50.0	212	47	25.3	2.43
91	1.13	45.9	198	56	27.7	1.70
92	0.76	47.6	125	57	29.3	2.62
93	1.38	51.4	260	61	33.5	1.84
94	1.09	51.3	194	57	31.4	2.32
95	0.98	52.4	227	49	27.6	2.74
96	0.84	34.8	120	56	21.4	1.75
97	1.19	58.5	256	60	37.3	2.41
98	1.10	49.7	150	57	30.1	2.32
99	0.99	38.7	153	59	24.9	1.94
100	1.08	42.4	190	48	22.1	1.84
101	1.13	43.7	212	64	30.4	1.71
102	1.13	62.5	167	61	40.0	2.49
103	1.48	61.3	162	75	48.3	2.28
104	1.41	62.8	255	65	42.9	2.27
105	1.36	63.2	169	65	43.5	2.72
106	1.28	63.9	170	58	38.9	2.43
107	1.11	53.0	212	63	35.7	1.91
108	1.48	59.6	155	73	46.3	2.11
109	1.12	56.0	207	72	43.0	2.65
110	1.27	59.9	185	68	42.9	2.56
111	1.32	57.8	187	68	41.8	2.27
112	1.42	55.7	168	67	39.6	2.32
113	0.84	36.8	97	58	23.5	1.52
114	1.03	44.6	110	68	32.8	1.95
115	1.32	57.7	171	69	42.3	2.13
116	1.23	53.5	182	62	35.6	2.24
117	1.50	73.2	350	67	51.7	3.01
118	1.37	57.5	170	66	40.1	1.88
119	1.28	56.7	160	70	42.1	2.06
120	1.01	53.9	172	45	25.9	2.56
121	1.40	59.5	166	68	42.6	2.31
122	0.81	45.7	205	56	27.7	2.56
123	1.45	60.7	197	45	29.1	2.08
124	1.03	52.8	173	51	28.5	2.60
125	1.04	52.4	159	66	37.1	2.58
126	1.14	58.0	172	54	33.4	2.48
127	1.19	52.3	178	69	38.3	2.10
128	1.10	46.2	270	44	21.9	1.87

Table 6 (Continued)

Tree number	d_{bh} (ft)	H_{bh} (ft)	Age (yrs)	Percent crown	H_c (ft)	τ (sec)
129	0.83	37.5	193	62	25.5	1.61
130	1.11	54.8	196	53	30.6	2.50
131	1.15	39.6	160	65	28.1	1.78
132	1.24	65.6	215	70	48.1	2.20
133	1.13	56.9	198	72	43.3	2.22
134	1.00	43.1	175	62	29.1	1.71
135	0.79	39.6	158	60	25.9	2.33
136	1.18	48.9	185	71	37.1	1.93
137	1.02	45.8	161	65	32.0	2.24
138	0.99	45.7	174	72	35.4	2.15
139	1.28	48.9	170	61	32.1	1.88
140	1.03	53.6	206	48	27.7	2.27
141	1.13	53.2	240	64	36.5	1.93
142	1.22	52.8	183	67	37.5	2.21
143	1.02	51.2	195	63	34.4	2.48
144	1.12	52.7	183	60	33.7	2.11
145	1.27	52.6	196	62	34.9	2.43
146	1.05	52.5	265	69	38.8	2.10
147	1.15	53.3	200	66	37.3	2.29
148	0.99	51.5	190	47	25.9	2.20
149	1.43	51.9	200	61	33.9	2.10
150	1.09	43.3	187	60	28.3	1.55
151	1.01	45.5	195	61	30.0	1.75
152	1.18	54.8	152	68	39.6	2.31
153	1.10	56.1	210	66	39.2	2.24
154	1.47	64.6	165	73	49.4	2.49
155	1.16	50.2	142	76	40.6	1.97
156	1.34	57.6	250	52	31.9	2.69
157	1.45	53.8	258	63	36.3	2.03
158	0.81	38.0	167	70	28.9	2.13
159	1.28	53.9	160	71	41.0	2.29
160	1.23	59.1	200	52	32.6	2.40
161	1.08	39.6	285	63	27.1	1.61
162	1.38	49.1	280	63	33.2	1.88
163	1.32	52.9	178	73	41.0	2.54
164	1.22	53.1	280	48	26.9	2.68
165	1.34	68.9	248	65	46.7	3.15
166	1.02	47.6	170	65	33.1	2.15
167	1.02	45.2	200	56	27.2	2.08
168	1.03	39.9	190	65	28.3	1.98
169	0.94	52.2	179	38	20.9	2.55
170	0.85	46.7	135	58	29.2	2.08

1/ Nomenclature given on page 36.

Table 7.--Experimental tree period data[1] for conifers (except ponderosa pine)

Tree number	Species	d_{bh} (ft)	H_{bh} (ft)	Age (yrs)	Percent crown	H_c (ft)	τ (sec)
1	Sugar pine	1.46	48.5	-	80	41.6	1.84
2	Lodgepole pine	1.48	53.5	52	80	45.6	2.13
3	Loblolly pine	0.41	38.5	19	40	16.8	4.92
4	" "	1.69	93.1	45	40	39.9	4.12
5	" "	1.27	68.8	28	50	37.8	4.09
6	" "	0.95	70.8	25	35	26.2	3.99
7	" "	1.11	70.0	31	40	29.4	4.78
8	" "	0.90	60.4	-	33	21.3	4.21
9	" "	0.85	67.9	-	24	17.3	5.21
10	White fir	1.48	78.5	39	80	65.6	3.09
11	Douglas-fir	1.04	60.0	62	80	51.0	2.76
12	Incense cedar	1.08	47.5	56	80	41.0	2.27
13	Engelmann spruce	1.07	80.2	102	66	56.2	3.96
14	" "	2.07	125.5	215	62	81.0	3.75
15	" "	0.57	32.3	78	85	31.3	2.25
16	" "	0.48	26.1	79	71	21.8	1.66
17	" "	0.99	59.6	101	76	48.8	2.74
18	" "	1.96	104.3	179	65	71.0	3.80
19	Western larch	0.64	42.3	34	64	30.0	2.68
20	" "	2.15	131.1	200	53	71.2	4.68
21	" "	1.02	81.5	86	44	38.0	5.35
22	" "	2.18	123.4	216	60	76.3	4.75
23	" "	0.47	37.0	30	76	31.7	3.15
24	" "	0.99	84.0	93	53	46.5	3.54
25	W. white pine	1.75	122.5	-	60	76.2	5.26
26	" " "	1.31	106.5	-	60	66.6	5.31
27	" " "	0.38	53.0	-	25	14.4	4.62
28	" " "	0.71	85.5	-	30	27.0	4.92

1/ Nomenclature given on page 36.

Table 8.--Experimental tree period data[1] for broadleafs and coconut palms

Tree number	Species	d_{bh} (ft)	H_{bh} (ft)	Age (yrs)	Percent crown	H_c (ft)	τ (sec)
1	Silver maple	0.90	56.1	62	77	45.7	3.14
2	" "	1.07	63.8	68	62	41.6	2.66
3	" "	1.16	58.2	58	52	32.3	2.78
4	" "	0.98	56.7	41	57	34.2	2.75
5	Sweet birch	0.60	62.1	38	58	38.0	4.45
6	" "	0.69	62.4	38	54	35.4	3.84
7	" "	1.04	74.1	-	57	44.0	4.36
8	" "	1.15	57.0	67	60	36.6	2.96
9	" "	0.93	66.9	56	66	46.4	4.32
10	" "	0.50	49.1	63	43	22.6	3.91
11	Pignut hickory	0.82	72.5	59	43	32.9	4.82
12	" "	0.67	52.2	32	49	27.2	4.79
13	" "	0.66	54.8	52	47	27.4	4.65
14	" "	0.52	47.4	51	51	26.1	5.58
15	" "	1.95	97.8	191	65	65.4	4.94
16	" "	1.02	78.6	49	51	41.7	5.80
17	American beech	0.66	54.7	43	77	45.0	4.38
18	" "	0.49	44.0	51	72	34.4	3.86
19	" "	0.80	56.8	62	79	47.7	3.31
20	" "	1.32	72.0	80	73	54.9	3.41
21	Yellow-poplar	0.51	64.6	33	31	20.9	4.39
22	" "	0.69	73.3	32	54	41.8	5.89
23	" "	1.05	85.0	43	41	36.3	4.67
24	" "	1.80	95.6	60	49	48.8	3.72
25	" "	0.88	81.4	46	52	44.1	5.27
26	" "	1.22	90.3	50	56	52.4	4.36
27	Scarlet oak	0.66	46.9	32	58	29.4	3.15
28	" "	0.98	69.4	64	49	35.5	5.69
29	" "	1.19	77.6	64	45	36.1	4.80
30	" "	1.68	88.3	104	46	42.4	3.94
31	" "	0.48	49.6	36	35	18.8	4.75
32	Pisonia	0.88	30.5	- [3]	29	10.0	2.22
33	"	0.92	35.5	-	38	15.0	2.42
34	"	1.16	40.5	-	45	20.0	2.00
35	"	1.27	35.5	-	38	15.0	1.92
36	"	1.02	37.5	-	41	17.0	2.14
37	"	0.88	30.5	-	29	10.0	2.48
38	Coconut palm	0.92[2]	40.7	-	80	35.7	2.47
39	" "	1.00	35.5	-	77	30.5	1.76
40	" "	0.88	39.0	-	79	34.0	2.39
41	" "	1.43	48.0	-	83	43.0	2.61
42	" "	1.04	32.5	-	70	25.5	1.78

1/ Nomenclature given on page 36.
2/ Diameters of coconut palms are at 5 ft. above ground level.
3/ Ages were indeterminate.

Table 8 (Continued)

Tree number	Species	d_{bh} (ft)	H_{bh} (ft)	Age (yrs)	Percent crown	H_c (ft)	τ (sec)
43	Coconut palm	0.89	33.5	-	81	30.5	1.78
44	" "	0.93	30.5	-	80	27.5	1.97
45	" "	0.97	48.5	-	90	43.5	2.27
46	" "	0.90	25.8	-	70	20.8	1.35
47	" "	0.95	18.3	-	63	14.0	1.64
48	" "	1.47	50.2	-	18	10.0	3.00
49	" "	1.06	41.0	-	27	12.0	2.51
50	" "	1.18	45.7	-	24	12.0	3.09
51	" "	1.14	30.9	-	34	12.0	2.18
52	" "	1.04	42.9	-	26	10.0	2.55
53	" "	1.18	40.4	-	27	12.0	2.60
54	" "	0.95	18.2	-	45	10.0	1.34
55	" "	0.98	16.0	-	50	10.0	1.90
56	" "	1.19	21.5	-	47	12.0	2.18
57	" "	0.98	34.4	-	26	10.0	2.52
58	" "	1.18	34.7	-	26	10.0	2.74
59	" "	1.00	26.7	-	33	10.0	2.17
60	" "	0.93	30.2	-	29	10.0	2.67
61	" "	0.89	27.2	-	24	10.0	2.29
62	" "	1.10	25.2	-	34	10.0	1.98
63	" "	1.08	26.7	-	33	10.0	1.96
64	" "	1.05	29.2	-	30	10.0	2.32
65	" "	1.02	29.1	-	30	10.0	2.58
66	" "	1.21	20.7	-	49	12.0	1.58
67	" "	1.09	36.5	-	27	12.0	1.75

1/ Nomenclature given on page 36.
2/ Diameters of coconut palms are at 5 ft. above ground level.
3/ Ages were indeterminate.

Table 9.--Experimental bare stem period data[1] for several tree species

Tree number	Species	d_{bh} (ft)	H_{bh} (ft)	τ (sec)	Tree number	Species	d_{bh} (ft)	H_{bh} (ft)	τ (sec)
1	Ponderosa pine	0.75	34.8	1.24	27	Pignut hickory	0.82	72.5	2.28
2	" "	0.79	37.8	1.48	28	" "	0.67	52.2	1.74
3	" "	0.42	14.6	0.81	29	" "	0.66	54.4	1.89
4	" "	1.25	55.2	1.51	30	" "	1.95	97.8	1.69
5	" "	1.90	56.0	2.21	31	" "	1.02	78.6	1.66
6	" "	3.08	120.5	2.56	32	American beech	0.66	54.7	1.27
7	" "	1.69	88.5	2.43	33	" "	0.49	44.0	1.12
8	Sugar pine	1.46	48.5	1.09	34	" "	0.80	56.8	1.18
9	Lodgepole pine	1.48	53.5	1.13	35	" "	1.32	72.0	1.15
10	Loblolly pine	1.69	93.1	2.00	36	Yellow-poplar	0.51	64.6	1.90
11	" "	1.27	68.8	1.66	37	" "	1.05	85.0	2.71
12	" "	0.95	70.8	2.05	38	" "	1.80	95.6	1.89
13	" "	1.11	70.0	1.96	39	" "	0.88	81.4	2.64
14	White fir	1.48	78.5	1.71	40	" "	1.22	90.3	2.36
15	Douglas-fir	1.04	60.0	1.55	41	Scarlet oak	0.66	46.9	1.21
16	Incense cedar	1.08	47.5	1.26	42	" "	0.98	69.4	2.04
17	Silver maple	0.90	56.1	0.99	43	" "	1.19	77.6	1.81
18	" "	1.07	63.8	1.20	44	" "	1.68	88.3	2.04
19	" "	1.16	58.2	1.20	45	Coconut palm	0.92[2]	40.7	1.18
20	" "	0.98	56.7	1.03	46	" "	1.04	43.5	1.34
21	Sweet birch	0.60	62.1	1.88	47	" "	1.00	35.5	0.90
22	" "	0.69	62.4	1.77	48	" "	1.43	48.0	0.94
23	" "	1.04	74.1	1.39	49	" "	1.04	32.5	0.50
24	" "	1.15	57.0	0.99	50	" "	0.89	33.5	0.75
25	" "	0.93	66.9	1.36	51	" "	0.93	30.5	0.61
26	" "	0.50	49.1	1.39	52	" "	0.97	48.5	1.35
					53	" "	0.90	25.8	0.50

1/ Nomenclature given on page 36.
2/ Diameters of coconut palms are 5 ft. above ground level.

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NOMENCLATURE

a = constant in regression equations

b = coefficient in regression equations

bh = breast height, 4.5 ft. above ground level

c = stem form or shape factor

d = diameter of stem at base, ft.

d_{bh} = stem diameter outside bark at breast height, ft.

E = modulus of elasticity, lb/in^2

f = a function

H_{bh} = height of stem above breast height, ft.

H_c = height of live crown, ft.

L = length of stem, ft.

r = coefficient of correlation

S_{yx} = standard error estimate, sec.

ρ = mass density, lb sec^2/ft^4

τ = natural period of tree or stem--time required for one complete cycle of oscillation, sec.